SIRAS, The Spaceborne Infrared Atmospheric Sounder: an approach to next-generation infrared spectrometers for Earth remote sensing

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ABSTRACT

The Spaceborne Infrared Atmospheric Sounder (SIRAS) represents a new approach to imaging spectrometry in the infrared by combining next generation wide field of view refractive/diffractive optics with high-dispersion gratings to minimize size and mass while improving spatial resolution. Prototype hardware was developed and tested on this program to demonstrate that high spectral and spatial resolution could be achieved in a package of small size and mass. The performance, development and testing of the prototype spectrometer are discussed as well as potential applications for future missions. This effort was sponsored under the NASA Instrument Incubator Program (IIP).

1.0 INTRODUCTION

The Spaceborne Infrared Atmospheric Sounder (SIRAS) is an instrument concept for an infrared imaging spectrometer operating in the 3.7 to 15.4 μm spectral region developed under NASA's Instrument Incubator Program (IIP). SIRAS was designed to meet the requirements of the Atmospheric Infrared Sounder (AIRS) instrument that is to be flown on the EOS-Aqua spacecraft, but in a smaller package and with higher spatial resolution (0.5 km vs AIRS 13.5 km). As such, the possibility of using SIRAS as follow-on to AIRS provides the possibility for continued global daily measurements of atmospheric water vapor and temperature with unprecedented resolution and accuracy.

The NASA Instrument Incubator Program has been established as a means to rapidly develop and demonstrate new technologies applicable to future Earth remote sensing science missions. The goal of IIP is to develop and demonstrate new technologies in a quick turn-around three-year program with the goal of having an instrument concept completed at this time that would be ready for space flight within three years.

The focus of the IIP hardware development undertaken in this program was the design, fabrication, assembly, and test of an infrared spectrometer. This IR spectrometer takes advantage of wide field-of-view refractive optics and a high-dispersion grating and demonstrates the smallest possible solid state (no moving parts) IR spectrometer system that can be made at these wavelengths and at this resolution. The focus of this effort was to develop and demonstrate one of the four-spectrometer subsystems making up the SIRAS instrument. This was the longest wavelength spectrometer, that designed to operate in the 12 to 15.4 μm spectral region. This effort included developing all optical and mechanical hardware necessary in a flight-like configuration.

Although the motivation for this IIP study was to develop an instrument concept suitable for Low-Earth Orbit (LEO), it was shown that the same spectrometer could also meet the requirements of a Geosynchronous (GEO) Sounder. A system concept was developed for this application that included scanning, passive and active cooling systems, the infrared spectrometers and fore optics, and focal plane arrays offering a system of comparable performance, yet with considerable size and mass savings when compared to alternate planned instruments.

2. INSTRUMENT INCUBATOR PROGRAM

The NASA Instrument Incubator Program (IIP) was established as a mechanism for developing innovative new technology concepts suitable for future NASA remote-sensing missions and as a means to demonstrate and assess these concepts in ground, aircraft, and engineering model demonstrations. IIP is funded through NASA's Office of Earth Sciences (OES). The goals set forth for an IIP program are to (1) develop and demonstrate mission development in less than thirty-six months; (2) develop the technology such that it is suitable for integration in an operational space instrument within eighteen months following the 3-year IIP development; (3) the instrument concepts developed under IIP must reduce instrument and measurement concept risk to allow the concept to be competitive in an OES Announcement of Opportunity; and finally, (4) the concepts shall enable new science and/or reduce instrument cost, size, mass and resource use.

SIRAS was one of twenty-seven proposals funded under the first IIP solicitation, and, in the opinion of the authors, has met the stated goals of IIP. More information on the Instrument Incubator Program can be found at the IIP web site: http://esto.gsfc.nasa.gov/programs/iip/.

3. SCIENCE REQUIREMENTS

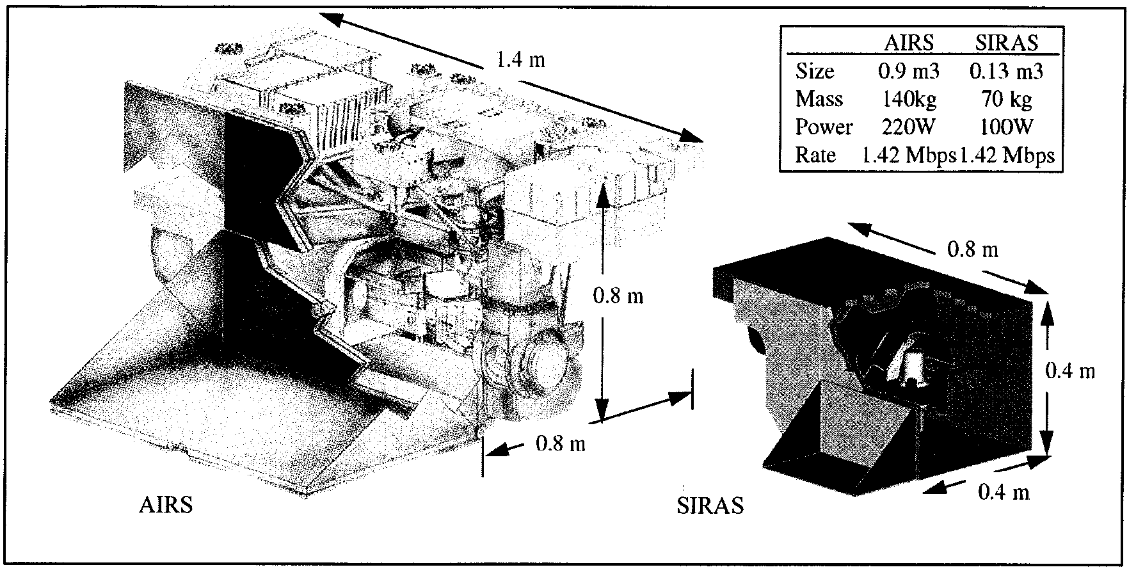
The Atmospheric Infrared Sounder (AIRS)[1] instrument currently under development for the EOS Aqua mission will demonstrate the importance of high resolution atmospheric infrared data to the science and operational communities. AIRS is a high resolution instrument that measures upwelling infrared (IR) radiances at 2378 frequencies ranging from 3.74 and 15.4 micrometers. AIRS will provide significant improvements in the accuracy and temporal resolution of several climate and weather parameters over current measurements. More information on the AIRS program can be found in other references from this symposium[2].

Key system-level performance requirements for AIRS are shown in Table 3.1.

Table 3.1 AIRS Performance Requirements

Orbit	705km
IFOV	1.1°, 13.5 km
Scan Range	±49.5 °
No. Spectral Bands	2378 (Nyquist Sampled) IR, 4 Visible
Spectral Range	3.7-15.4 μm, 0.425 μm, 0.63 μm, 0.82 μm, 0.73 μm
Spectral Resolution	1200 (nominal)
On-Board Calibration	Space View, Full Aperture Blackbody, Parylene Spectral
Primary Measurement	Atmospheric Temperature and Water Vapor, Surface Temperature

The benefits demonstrated by AIRS must be carried over to scientific and operational systems to provide the long-term data base of continuous observations required for climate studies and the continued ability to improve weather forecasting. However, AIRS is considered too large and too demanding of spacecraft resources to be easily accommodated on future NASA or NPOESS missions. SIRAS is intended to address these shortcomings by providing the required performance in 15% of the volume and 50% of the mass. The AIRS covers the 3.7 to 15.4 μm region using an all-reflective single grating spectrometer. The SIRAS approach, shown in Figure 3-1, is to use four smaller grating spectrometers with refractive optical systems. Each spectrometer covers a larger field of view spatially, thereby allowing a 4x reduction in lens diameters while preserving radiant throughput (A-Omega product). Dividing the spectral coverage into four ranges and operating in lower diffraction orders also greatly eases the out-of-band rejection filter requirements and simplifies the focal plane design.



	AIRS	SIRAS
Size	0.9 m3	0.13 m3
Mass	140kg	70 kg
Power	220W	100W
Rate	1.42 Mbps	1.42 Mbps

Figure 3-1. Potential volume and mass reduction offered by SIRAS

4. SIRAS SYSTEM OVERVIEW

The flight instrument concept for SIRAS has four spectrometer modules that cover the 3.4 to 15.4 μm spectral region. The spectral bands are broken out as shown in Table 4.1. A barrel-scan mirror provides the ground coverage, and a single reflective fore-optic serves to focus the scene energy onto the slit. Scene radiation is then split into four separate spectrometer modules via beamsplitters.

The requirement for low background requires that the spectrometer modules all be cryogenically cooled to 140 K, and the focal planes to 60 K. Active cooling of the detectors is proposed for the flight instrument configuration using a split-sterling pulse-tube cooler. SIRAS has been developed to use the same focal plane arrays as AIRS[3]. These are PV HgCdTe arrays developed by Lockheed Martin Sanders (now BAE Systems).

The focus of the SIRAS IIP was to demonstrate that the performance requirements from AIRS could be met in a smaller, lighter, and less costly system. Our primary goal was to demonstrate that the required spectral resolving power, spatial resolution, and high optical throughput could be achieved in the SIRAS instrument. The most demanding aspect of this was demonstrating that a spectral resolving power ($\lambda/\Delta\lambda$) of between 900 and 1400 could be met.

The technology demonstration undertaken was to develop a laboratory demonstration spectrometer that would demonstrate that the key performance requirements could be achieved. We selected the longest wavelength spectrometer (spectrometer 4 in Table 4.1) since it represented the greatest challenge from the standpoint of manufacture and test, and in keeping with the IIP objectives, the spectrometer was built to the flight configuration

The SIRAS laboratory demonstration unit and major components are shown in Figure 4-1. A PV HgCdTe multiplexed detector array was provided on loan from the AIRS program. The major optical components are broken out into three subsystems: the collimator, the grating and the camera.

Table 4.1. Preliminary design parameters for the flight SIRAS

Parameter	Units	Spectrometer Number			
		1	2	3	4
λ_{min}	(μm)	3.7	6.2	8.8	12
λ_{max}	(μm)	4.61	8.22	12	15.4
Avg. Sampling	(-)	2200	2200	2200	2200
Avg. Res	(-)	1100	1100	1100	1100
Order	(-)	2	2	1	1
Incidence	(deg)	45	45	45	45
Avg. Disp	(rads/μm)	0.2677	0.1534	0.1082	0.0832
Field of View	(deg)	13.957	17.752	19.844	16.201
F-Number	(-)	1.70	1.70	1.70	1.70
Aperture Size	(cm)	2.94	2.94	2.94	2.94
Resolution.	(mr)	0.1723	0.2991	0.4314	0.5683
Detector Size	(μm)	25	25	25	25
No. Channels	(-)	487	620	693	566
FPA-Length	(cm)	1.22	1.55	1.73	1.41

Interface electronics for the FPA were provided by LM Sanders on loan to BATC for the IIP program. Computer interface electronics and software were developed by BATC for capture of the data onto a PC. All hardware development and testing was conducted at BATC.

All spectrometer-level testing was performed in a thermal-vacuum chamber operating at cryogenic temperatures to limit background flux falling on the detectors. Sources were viewed through a zinc selenide window and included a collimator and source assembly for spatial performance tests; and a blackbody for radiometric performance testing.

5. OPTICAL SYSTEM

A compact optical design was developed for the SIRAS spectrometer modules. The laboratory demonstration spectrometer design is shown in Figure 5-1. This design form, while not necessarily using the same optical materials, is easily extendable to the other three spectral regions. An all-refractive design was selected for the spectrometer since this design form could be developed in a smaller, lower-cost package than an all-reflective design developed to the same requirements.

Optical material choices are limited in the 12 to 15.4 μm region, particularly when one wants to get uniformly high transmission over the spectral band. A number of materials, several that are routinely used in applications in the longwave IR, including germanium and zinc sulfide, were deemed unsuitable since they exhibit excessively high internal absorption at wavelength greater than ~14 microns. Figure 5-2 shows measured transmission curves for several optical materials suitable for this region in the LWIR. It should noted, that in addition to good transmission, we also choose to limit our material selection to those materials that exhibit reasonably good mechanical, thermal and handling properties. Therefore, materials such as cesium bromide and potassium bromide were eliminated from consideration. It is readily apparent from this graph that of the materials identified, zinc selenide, cadmium telluride, and thallium bromoiodide (KrS-5) exhibit the best transmission properties for this spectral region, and accordingly, these were the materials selected.

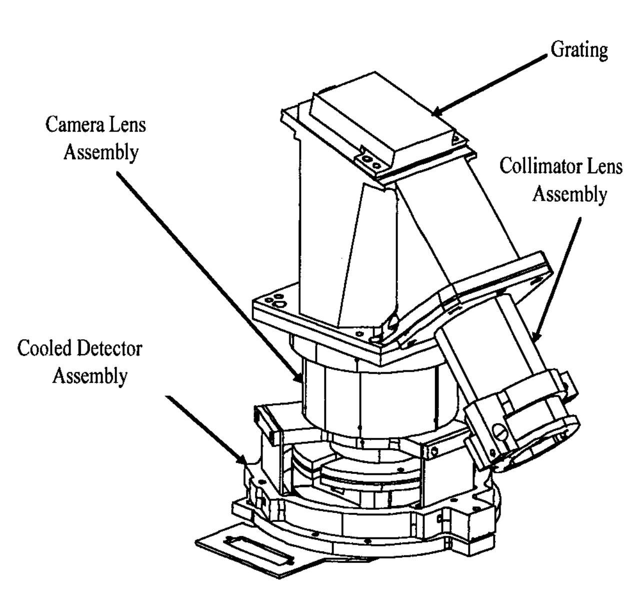


Figure 4-1. SIRAS Laboratory Demonstration Instrument

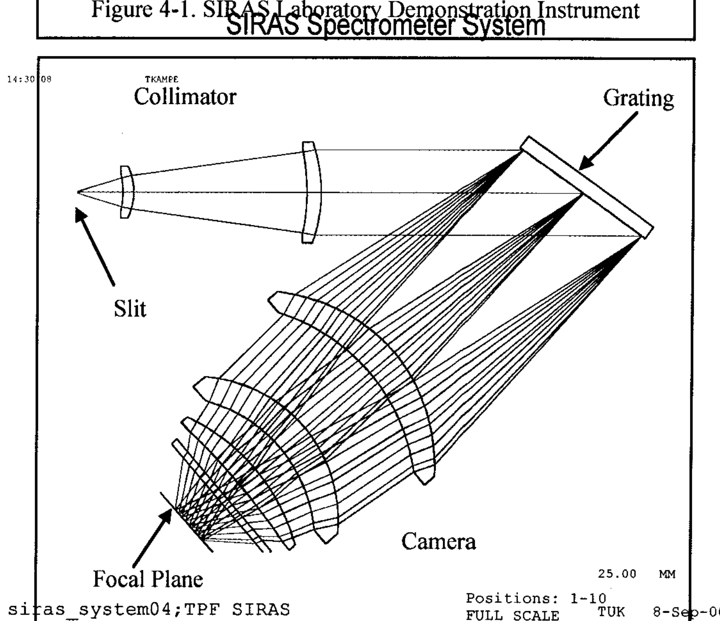


Figure 5-1. SIRAS Long-wave Spectrometer Optical Configuration

The spectrometer optical system is functionally broken out into three optical subsystems. The collimator intercepts diverging radiation that has passed through the slit and provides collimated radiation to the grating. The grating specified for this application is a linear blazed grating operating at 45^0 and used in the first diffraction order. The final optical subsystem is the camera. This refractive lens group serves to image radiation diffracted off the grating onto the focal plane array.

The SIRAS spectrometer operates at 140 K to reduce background radiation; therefore, the thermal properties of the optical materials must be accounted for since it is desirable that the spectrometer remains in focus from ambient to operational temperature.

As such, we set a goal to develop the refractive optical subsystems as athermal systems. This was achieved for the collimator but not the camera, necessitating a focus adjustment of about 0.43 mm when going from ambient to 140 K.

Aluminum was selected as the mount material for the laboratory demonstration SIRAS spectrometer principally based on low cost and ease of fabrication. The collimator, shown in Figure 5-3 was designed as a two-element objective, with zinc selenide and KrS-5 as the optical materials. A hybrid diffractive/aspheric profile was incorporated on the zinc selenide element. The combination of the negative dn/dt of KrS5 and the diffractive surface allowed us to athermalize the system and keep it in focus over the full temperature range.

Since the collimator is used over the full 12-15.4 μm spectral band, it was necessary to maintain good color correction as well. That this was achieved can be seen from the transverse ray aberration plots in Figure 5-4. The collimator operates at F/1.7 and covers a 1.1^0 field-of-view. The collimator is diffraction-limited and exhibits essentially no degradation in performance with temperature (Figure 5-5).

The hybrid diffractive/aspheric profile on the zinc selenide element requires a second-order phase coefficient and fourth and sixth-order aspheric terms and was diamond single-point machined onto the base spherical surface. A key point, often overlooked with diffractive elements is the amount of radiation lost due to tool blockage that results from the inherent inefficiencies in the fabrication of "stepped" diffractive surfaces. For this element, there were thirteen diffractive zones. Riedl[4] presents the following expression for estimating tool blockage losses:

$$L = \frac{4}{D}\sqrt{\frac{2dR_t}{\eta_{total}}} * \sum_{\eta}^{\eta_{total}} \sqrt{\eta} \qquad (1)$$

where: L = transmission due to tool blockage

D = lens diameter

d = zone depth

η = number of zones

R_t = tool radius

In the case of this element, a transmission loss resulting from tool blockage of less than 6% was required. This necessitated using a diamond tool with a radius of 0.20 mm or smaller. This was achieved, but required special effort on the part of the lens fabricator. It is important to understand that a trade-off exists when pushing for minimal transmission losses and that is increased surface roughness that results from using a smaller tool.

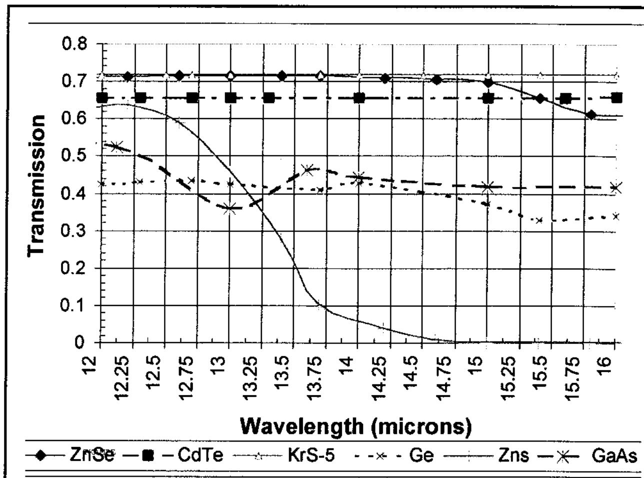


Figure 5-2 Material Transmission Properties

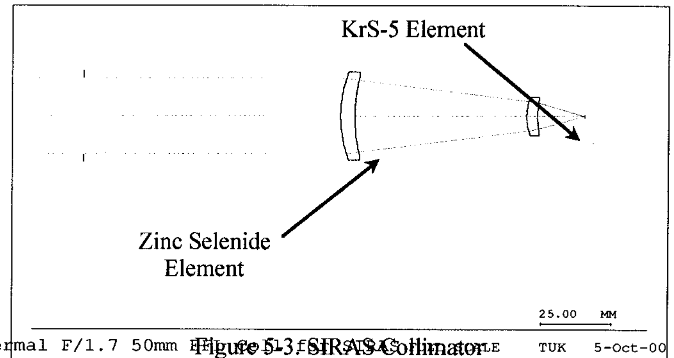


Figure 5-3 SIRAS Collimator

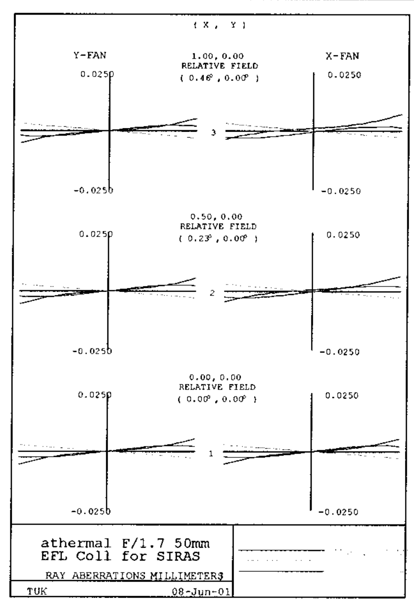


Figure 5-4. Collimator Rim Rays

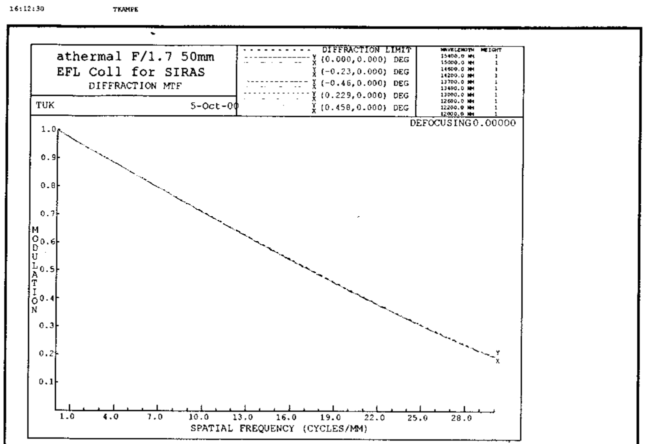


Figure 5-5(a). MTF at Ambient

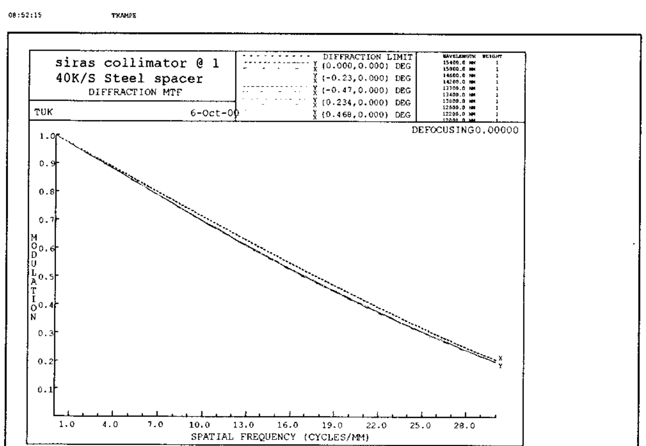


Figure 5.5(b). MTF at 140 K

Again from Riedl[4] , the surface roughness of a diamond-machined surface can be estimated from the equation:

$$h = \left(\frac{1}{8R_t}\right)\left(\frac{D}{2PT}\right)^{0.5} \qquad (2)$$

where: h = P-V surface roughness
P = revolutions/minute of machine tool
T = cutting time in minutes

A surface roughness of 190 angstroms (P-V) was estimated for this component assuming the tool radius stated previously. This was felt to be adequate from a stray light standpoint in an IR application such as this. A Taleysurf profilometer trace of the diamond-turned surface is shown in Figure 5-6.

The spectrometer magnification is 1:1, therefore the camera focal length and F/# are identical to the collimator. However, the camera must cover a significantly larger field-of-view (16^0) since it passes the dispersed radiation to the focal plane. As such, the camera is a three-element objective composed of two zinc selenide elements and a cadmium telluride element. It too exhibits near diffraction-limited performance over the required spectral band.

Anti-reflection coatings (AR) are required to obtain the desired transmission in IR systems, particularly when using high index materials. AR coatings were developed for all the SIRAS optical elements, including the KrS-5 element in the collimator, and the cadmium telluride element in the camera. There were particular concerns with coating adhesion to the KrS-5 element but this did not prove to be a problem. Instead, adhesion on the cadmium telluride did prove to be a problem. Given the limited funds on this project, we chose to allow somewhat greater surface reflection losses in trade for a reduced number of coating layers. In a flight instrument, a more diligent coating development effort for cadmium telluride elements would be undertaken.

Representative measured surface reflectances and transmissions for the zinc selenide, cadmium telluride and KrS-5 substrates are shown in Figure 5-7.

6. OPTOMECHANICAL CONSIDERATIONS

Just as each of the refractive optical subsystems of the SIRAS spectrometer was designed independently, so were the lens barrels for each. This allowed for each optomechanical subassembly to be assembled and tested prior to integration. This allowed us to verify the performance of each subassembly before initiating the full spectrometer test sequence. A knife-edge response test was performed on both the collimator and the camera prior to and after bonding the elements into their respective lens barrels. These tests provided knife-edge response measurement (optical resolution) and a measure of flange focal distance. These tests were felt to be of particular importance since the hybrid diffractive/aspheric elements were being used and it was felt necessary to confirm that these had been properly manufactured before fully assembling the system. Several knife-edge scans for the collimator are shown in Figure 6-1. The measured performance for this sub-assembly was very near the predicted value.

Of principle concern in designing the mechanical system to house a refractive system to operate (and survive) over wide temperature ranges is ensuring that that compressive stresses exerted by the (aluminum) housing on the optics do not distort of damage the optical components. An elastometer bond with sufficient cell to lens gaps was incorporated into the SIRAS laboratory spectrometer. The elastometer chosen for this application has been tested at Ball Aerospace and

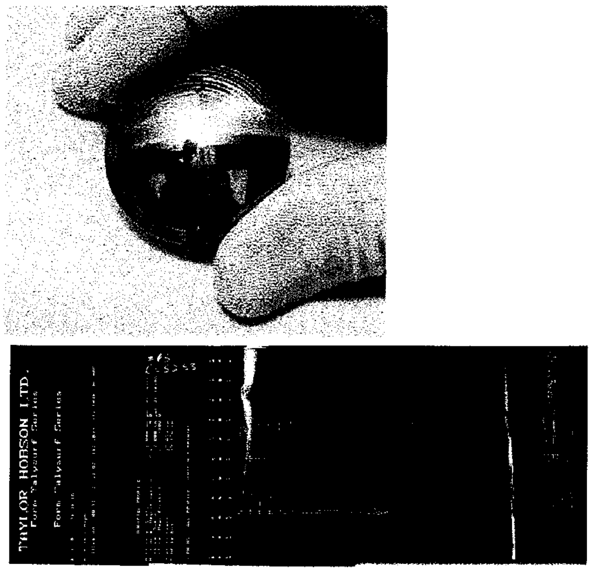


Figure 5-6 Diamond-turned Surface Profile

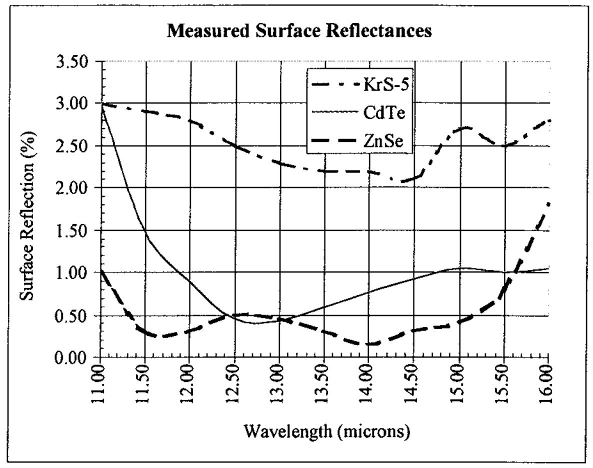


Figure 5-7 Anti-reflection Coating Performance

Technologies Corp (BATC) and shown to remain sufficiently compliant at cryogenic temperatures and exhibits low-outgassing properties.

Prior to subjecting the SIRAS spectrometer to the large temperature delta of going from ambient (~295 K) to 140 K, we chose to build a mass model and used it for testing purposes. The mass model had two purposes; first, we wanted to ascertain how long it would take to cool the spectrometer to 140 K, and secondly, by mounting two "scrap" lens elements in the mass model we could demonstrate the feasibility of our lens mounting approach. The mass model, a block of aluminum of equal mass and painted black in a similar manner as the laboratory demonstration SIRAS spectrometer, was mounted in a 18" thermal-vacuum chamber in the IR test facility at BATC. The mass model is shown in Figures 6-1 and 6-2.

No breakage to the optical elements were observed and the cool down cycle for the thermal-vacuum test was optimized such that a stable thermal environment at the desired test temperature was achieve in approximately twenty hours.

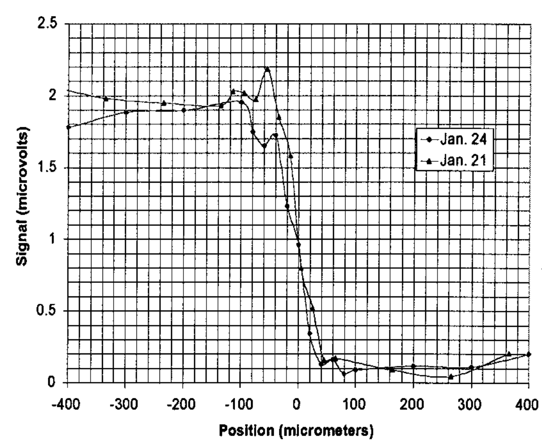


Figure 6-1 Knife-edge scans for collimator

All mechanical components, except for lens seats and mating surfaces, for the SIRAS laboratory demonstration spectrometer were painted with a high emissivity black paint. This was done to reduce the potential of stray light on internal surfaces, and to improve radiative thermal transfer on external surfaces.

The spectrometer housing served as the mounting interface for the FPA. Good mechanical registration of the FPA to the spectrometer is needed to focus and lateral positioning. However, the FPA needed to be thermally decoupled from the spectrometer housing . Thermal isolation was provided by fiberglass standoffs.

7. TESTING AND MEASURED PERFORMANCE

Testing at the spectrometer level was performed to determine spectral resolution (resolving power), wavelength calibration and wavelength dispersion. Testing was conducted in the Infrared Test Facility at Ball Aerospace and Technologies, Boulder, Colorado. The SIRAS laboratory demonstration spectrometer was mounted in a test cryosat shown in Figure 7-1.

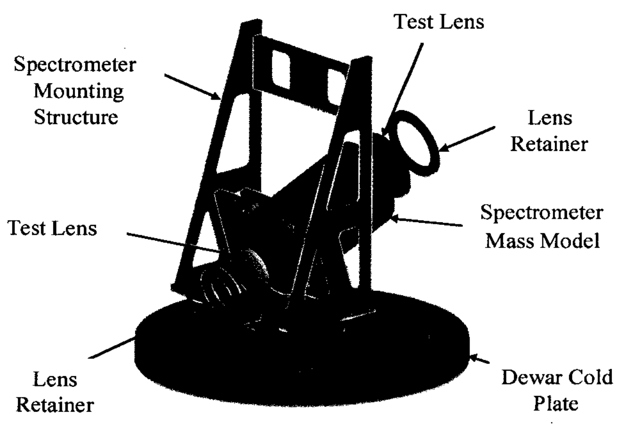


Figure 6-3 Mass model – parts breakdown

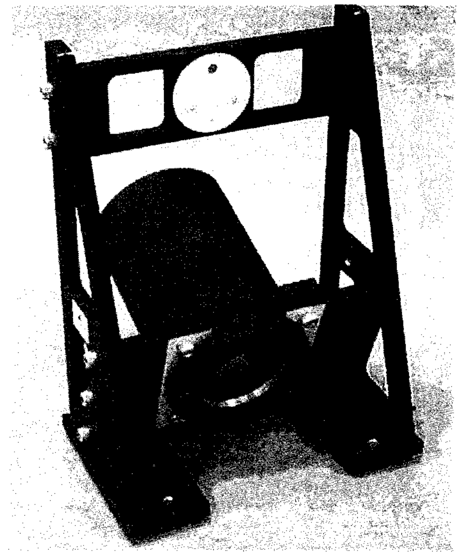


Figure 6-4 Mass model mounted in test fixture

The system was fully instrumented to monitor the temperatures of the optics, detector array, radiation shield, and cryosat surface. The diffraction grating, off-axis gold-coated paraboloid, and much of the (disconnected) wiring are visible.

Initial testing was required to adjust the spectrometer focus. Because the spectrometer operates in IR wavelengths only and must be cooled to cryogenic temperatures, there is no direct method to adjust focus (FPA location) while operating. The procedure was to start with the subsystem focus measurements and fabricate shims for the estimated focus shift with temperature. After the spectrometer was cooled to the operating temperature, an estimate of dispersion was obtained from the measured spectrum of blackbody radiation that passed through a spectrally-selective element. The correct focal length is calculated and shims selected to match the true EFL position. Several iterations of shimming, cooling, testing, and warming were required before a satisfactory focus was reached. Once a satisfactory focus position was reached, a more complete set of spectral measurements was conducted.

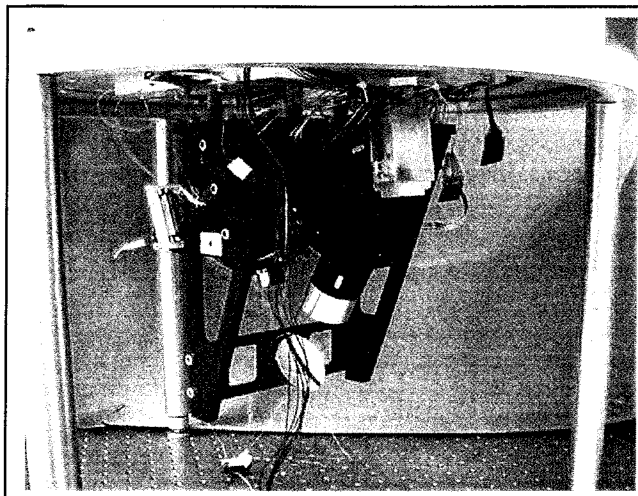


Figure 7-1 Photograph of SIRAS Laboratory Spectrometer in low-background test cryosat

The approach for dispersion measurement was to use a 1050 K blackbody and a series of spectral line filters placed in the optical path for a relative transmittance measurement. Spectral centers were then inferred from the locations of known spectral features.

Spectral resolution was determined using a differential air-path measurement. Figures 7-2 and 7-3 depict the test methodology. A reference spectral signal frame was obtained with the chopped blackbody source very near to the cyrosat window. A second spectral signal frame was then obtained with the blackbody at a known distance. The relative transmittance of the air path is the ratio of the two curves. The data were analyzed for spectral resolution by convolving a theoretical atmospheric transmission spectra with varying spectral response widths. The response widths were varied until the resulting convolved modeled spectra matched the measured spectra. The results indicate that the SIRAS spectral resolution is 1200 ± 300. The comparison of measured and modeled spectra is shown in Figure 7-4.

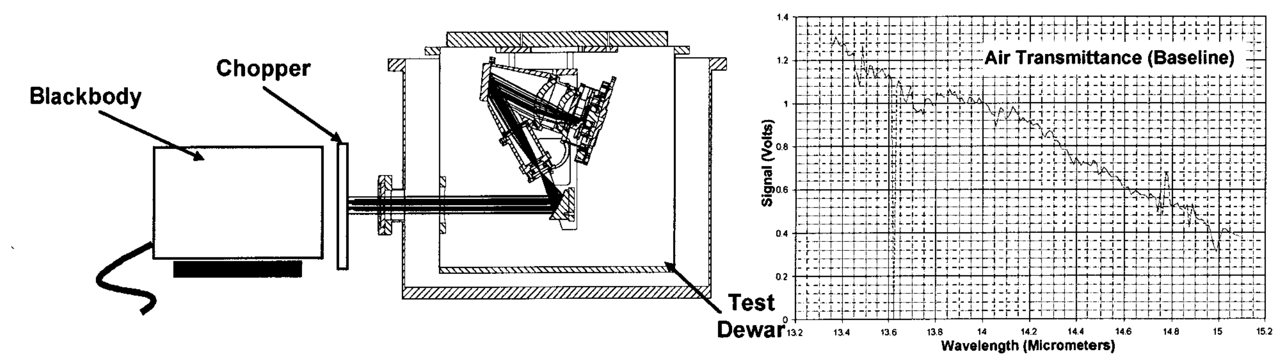
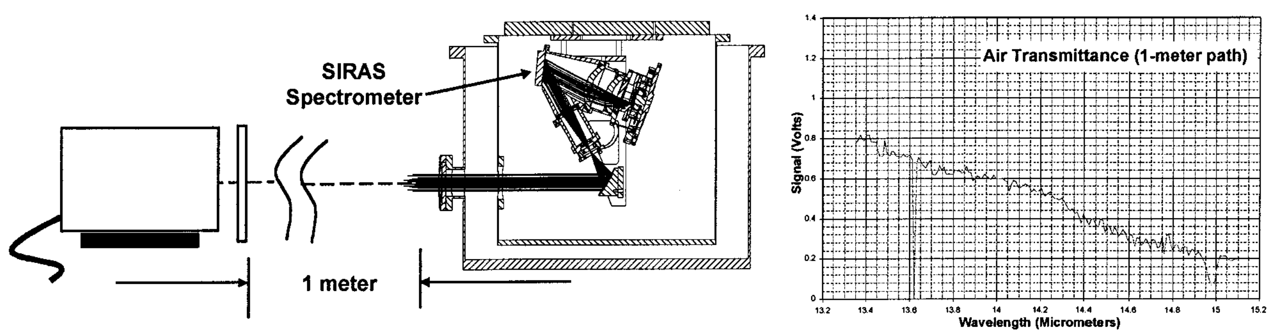


Figure 7-2. Spectral Response measure with blackbody in near proximity to dewar



Step 2: Spectral Response measured with blackbody moved 1 meter away from test dewar

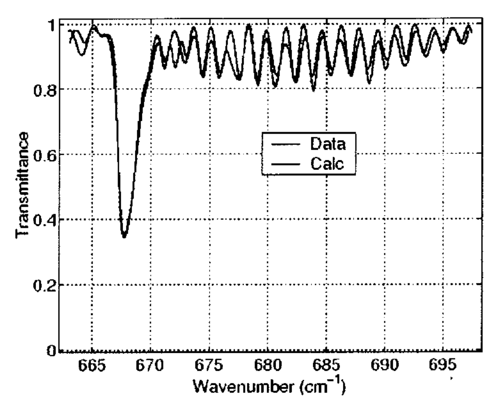


Figure 7-4. Comparison of measured spectra to modeled atmospheric transmission

8. CONCLUSIONS

A grating-based instrument concept has been developed suitable for space-based atmospheric sounding applications. The longest wavelength spectrometer of the SIRAS system was developed and tested under the NASA Instrument Incubator Program has been used to demonstrate that the desired spectral and spatial resolution is obtainable. The SIRAS is a compact high-performance instrument concept suitable for next-generation missions aimed at providing continued atmospheric data for long-term climate change research. In addition, SIRAS has applications in a number of other remote sensing areas including potential geosynchronous missions.

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